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Characterization of Polyurethane Systems Which Contain Low Levels of Free TDI

R. L. Myers, E. V. Thomas

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CHARACTERIZATION OF POLYURETHANE SYSTEMS WHICH CONTAIN LOW LEVELS OF FREE TDI

R. L. Myers
Organic Materials Department
and
E. V. Thomas
Statistics and Human Factors Department
Sandia National Laboratories
Albuquerque, NM 87185

Abstract

EN-7, EN-8, and EN-9 are polyurethane systems that are used in numerous applications in the Department of Energy complex. These systems contain high levels of toluene diisocyanate (TDI). Currently, TDI is being treated as a suspect human carcinogen within the Department of Energy complex. This report documents the results of a material characterization study of three polyurethane systems that contain low levels of free (potentially airborne) TDI. The characterization has been accomplished by performing a set of statistically designed experiments. The purpose of these experiments is to explore the effects of formulation and cure schedule on various material properties.

In general, the material properties (pot life, glass transition temperature, hardness, and tear strength) were relatively insensitive to variation in the cure schedule. On the other hand, variation in curative level had measurable effects on material properties for the polyurethane systems studied. Furthermore, the material properties of the three low-free-TDI polyurethane systems were found to be comparable or superior (for certain curative levels) to commonly-used polyurethane systems. Thus, these low-free-TDI systems appear to be viable candidates for applications where a polyurethane is needed.

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I. NIOSH Findings Indicate TDI Suspect Carcinogen

EN-7, EN-8, and EN-9 are polyurethane systems that are used in numerous applications in the Department of Energy Weapons Complex. These systems contain high levels (>10%) of toluene diisocyanate (TDI). Recent findings by the National Institute for Occupational Safety and Health (NIOSH) show correlations between exposure to TDI and cancer in animals. If TDI is regulated in the future by OSHA, the maximum amount of free TDI allowed in a polyurethane system is expected to be set at 0.1%; any system which contains a higher level of free TDI will require extensive regulatory controls in worker protection. Currently, TDI is being treated as a suspect human carcinogen within the Department of Energy Weapons Complex. The goal of this project, which is part of Sandia's Environmentally Conscious Manufacturing Program, is to minimize the use of potentially hazardous polyurethanes through the identification and characterization of suitable replacements.

This report documents the results of a material characterization study of three polyurethane systems that contain low levels of free (i.e., potentially airborne) TDI. The characterization has been accomplished by performing a set of statistically designed experiments. The purpose of these experiments is to explore the effects of formulation and cure schedule on various material properties. This document provides appropriate summaries of the experimental results with interpretations. The appendices provide the experimental test data.

II. Working Group Formed to Replace Cyanacure

The Alternate Polyurethane Systems Working Group was established in May 1990 with the original intent to find a replacement for Cyanacure, a polyurethane curing agent that was discontinued by the American Cyanamid Company due to the unavailability of a key raw material. This decision by American Cyanamid was motivated by economic issues, not by environmental or health concerns. About one year after its formation, the working group broadened its emphasis to include polyurethane systems which contain low levels of free TDI. Several polyurethane systems were selected and a set of screening tests were created (see below) to identify the promising systems for further characterization. The working group members divided the list of promising polyurethane systems in order to conduct further characterization of these systems.

Screening Tests for Polyurethane Systems

1. Review of Toxicological Data
2. Hardness (Shore A)
3. Pot Life: Viscosity vs. Time at 25°C (77°F), 71°C (160°F), and 93°C (200°F)
4. Modulus vs. Temperature for range: -54°C (-65°F) to 71°C (160°F)
5. Check for incompatibility with silicones

In other efforts, the working group investigated the feasibility of producing Cyanacure at AlliedSignal Aerospace/ Kansas City Division due to the uncertainty of pending regulations and concerns for future availability of materials.

The working group members are from Sandia National Laboratories (New Mexico and California), Los Alamos National Laboratories, Lawrence Livermore National Laboratories, Martin Marietta Energy Systems Y-12, AlliedSignal Aerospace/ Kansas City Division, EG&G Mound, Mason & Hanger Pantex Plant, and Martin Marietta Specialty Components Pinellas Plant. The work reported in this document has been done in conjunction with the efforts of the Alternate Polyurethane Systems Working Group members.

III. Statistical Approach Used in Materials Characterization

The focus of this study is to investigate the effects of varying the formulation (composition) and cure schedule (processing) on the material properties (e.g., pot life, hardness, tear strength, and glass transition temperature) of three polyurethane systems (listed in Section IV). An efficient way to conduct these investigations is through the use of statistically-designed experiments. Unlike many seat-of-the-pants experimental strategies, statistically-designed experiments provide useful information and reliable conclusions at minimum cost. Furthermore, there are a number of well-documented statistical design strategies that are appropriate for various objectives, such as: (1) identification of important factors (screening designs), (2) estimation of the magnitude of factor effects, singly or in combination (full-factorial designs), and (3) optimization of a process (response surface designs).

Here, our primary objective is to estimate the effects (including interactions) of the key factors that define the fabrication of polyurethane products. Our secondary objective is to identify processing conditions that lead to acceptable product, with material properties that are relatively invariant with respect to small perturbations from the identified processing conditions. Materials that are processed at such conditions will be easier to produce (hence cheaper), and will tend to have less variability in performance -- meaning less nonconformance and therefore higher quality. Thus, the ultimate objective of this experiment is to define a process that will produce quality materials at a reasonable cost. Furthermore, the information obtained in this study will allow us to conduct effective troubleshooting in future applications where errors have occurred in processing.

The development of an experimental design, relative to a particular objective, requires a full understanding of all processes involved, including the procedures used to prepare the materials and to measure the material properties. The preparation of polyurethane products involves specifying a composition (a binary mixture of prepolymer and curative) and the cure conditions (cure time and cure temperature). Thus, the number of key factors involved in preparing polyurethane products is three: the two factors associated with cure conditions and the single factor that describes the composition (e.g., % stoichiometry as given in parts by weight curative). The fact that there are only three factors involved in this process makes it possible to perform an in-depth study on these three factors utilizing relatively few experimental trials. This study, described herein, is capable of addressing the objectives stated earlier.

IV. Three Candidate Systems Identified for Study

All of the polyurethane systems in this study are 2-part, castable elastomer systems. The control system and the three alternative polyurethane systems are:

(1) Adiprene L-100/ Cyanacure (Ad/C), the control system,

(2) Adiprene L-100/ Ethacure 300 (Ad/E),

(3) Airthane PET 90-A/ Cyanacure (Ai/C), and

(4) Airthane PET 90-A/ Ethacure 300 (Ai/E).

The physical properties are given in Table 1 for the prepolymers and in Table 2 for the curatives. As can be seen in Table 1, both the Adiprene L-100 and the Airthane PET-90A prepolymers contain less than 0.1% free TDI, so both are preferable to EN-7, EN-8, and EN-9 in minimizing worker exposure to TDI. However, if OSHA regulates TDI at a maximum of 0.1%, then Airthane PET-90A will be the only prepolymer which meets this requirement since its manufacture (Air Products) has a patented process to guarantee a level of free TDI less than 0.1%. The manufacturer of Adiprene L-100 (Uniroyal) cannot make the same guarantee, so it is possible that the level of free TDI in a particular batch could exceed the regulatory limit. Limited information about the properties of the control system (Adiprene L-100/ Cyanacure) is available from earlier studies and will be covered in the discussion of the data.

Table 1
Properties of Prepolymers

Property	Adiprene L-100	Airthane PET-90A
% NCO:	3.9 - 4.3	3.5 - 3.7
Product Form:	Liquid[1]	Liquid[2]
% Free[3] TDI:	0.09[4]	0.05[4]
Viscosity, cps at 30°C (86°F)	16,000[4]	8,200[4]
Specific Gravity:	1.1	1.0

1. Prepolymer will solidify after several weeks (reconstitution necessary).
2. Prepolymer will solidify after 2 - 3 days (reconstitution necessary).
3. The term "free" implies "potentially airborne."
4. Data courtesy of F. N. Larsen, ASA/KCD

Table 2
Properties of Curatives

Property	Cyanacure	Ethacure 300
Equivalent Weight:	138	107
Molecular Weight:	276	214
Product Form:	Light tan flakes	Liquid
Melting Point:	74 - 76°C (165 - 169 °F)	N/A
Boiling Point:	N/A	353°C (667°F)
Flash Point, PMCC:	N/A	176°C (349°F)
Specific Gravity at 20°C:	N/A	1.2

To further develop the experimental strategy, we needed to specify the experimental regions to be studied for each of the polyurethane systems. Based on knowledge of related polyurethane systems and other chemical data, we were able to specify relatively large compositional and processing regions (see Figure 1) in which we expected to obtain suitable material properties. We verified the feasibility of the experimental regions by fabricating samples and testing them for the proposed responses: pot life, hardness, tear strength, and glass transition temperature (T_g).

The polyurethane plaques were made by hand-mixing the degassed prepolymer and curative, evacuating the mixture, and pouring the material into two stainless steel plaque molds. The material was degassed again before placing the molds in an oven to cure. The oven was programmed with the cure temperature and cure time for each condition. Each batch produced two 6"× 6"× 0.125" plaques. After the plaque molds were placed in the oven, the operator monitored the pot life on the material which was left in the mixing container. One particular operator was assigned to do all of the mixing for this study to maintain consistency in pot life determination. The samples were aged at least seven days at room temperature in a desiccator before testing for hardness, T_g and tear strength.

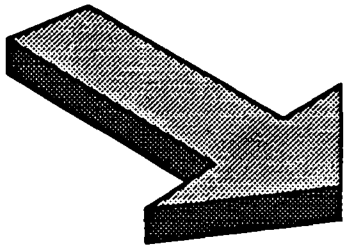
The hardness was measured using a Shore A durometer per the guidelines given in ASTM-D-2240; each value presented in this document represents the average of three measurements taken from the same plaque. The tear strength samples were fabricated and tested per the guidelines given in ASTM-D-624 (Die C). Each tear strength value given in this report represents the average of approximately ten measurements. The tear strength testing was done on an Instron test machine.

In the preliminary tests, we discovered that the method of thermomechanical analysis (TMA) was not able to produce accurate T_g values for the upper limit of the curative amount. Therefore, dynamic mechanical thermal analysis (DMTA) was chosen as the method for measuring the T_g values. The DMTA data was obtained using a Polymer Labs Inc. instrument using a frequency of 1 Hz and a heating rate of 3°C/minute with a dual cantilever holder. The preliminary testing showed this method to be an acceptable method for all curative levels for each material.

The specified compositional and processing regions, for each system, are indicated in Table 3. Notice that the ranges with respect to cure conditions are relatively wide and are consistent across all systems. In contrast, the compositional ranges vary from system to system; the high and low values correspond to the upper and lower limits of the stoichiometry range as given in Figure 1.

Figure 1. Factors/Responses Associated With Statistically Designed Experiment

Factors:
% Stoichiometry: 80% to 130%
Cure Temperature: 75°F - 212°F
Cure Time: 48 hours - 4 hours



Responses:
Pot Life
Hardness
Tear Strength
Glass Transition Temperature (T_g)

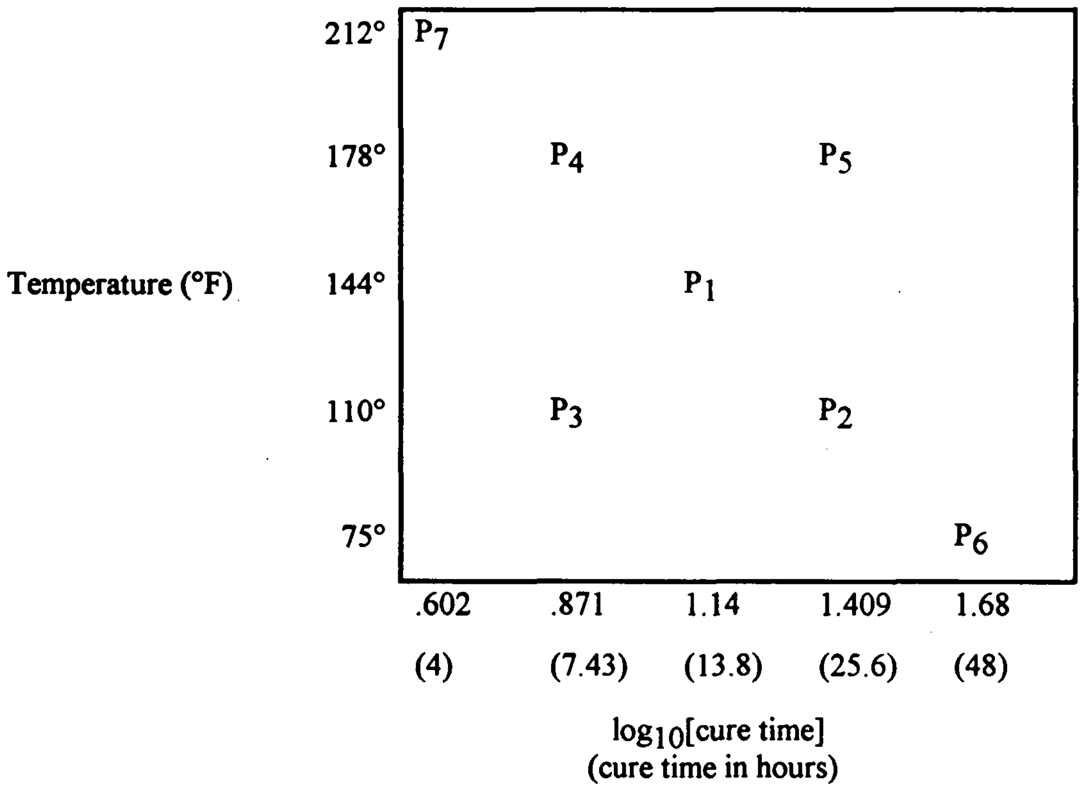
Table 3
Experimental Regions for Composition and Processing

System	Parts Curative[1]		Cure Time (hrs)		Cure Temp(°F)	
	Low[2]	High[3]	Low	High	Low	High
Ad/C	10.8	17.5	4	48	75	212
Ad/E	8.4	13.6	4	48	75	212
Ai/C	9.3	15.2	4	48	75	212
Ai/E	7.2	11.8	4	48	75	212

1. Parts (by weight) curative per 100 parts prepolymer
2. Corresponds to 80% Stoichiometry
3. Corresponds to 130% Stoichiometry

A separate, but similar, pattern of experimental trials was developed for each of the four polyurethane systems. The relatively small number of experimental factors (3) simplified this process considerably. Based on our objectives and earlier studies, we decided that three levels of the compositional factor would be adequate. The three levels consist of the two extremes and the midpoint between the two extremes. For each composition, we wanted a reasonably complete assessment of the effects of the two processing factors. Therefore, we decided to process each composition at each of the seven conditions ($P_1, P_2, ..., P_7$) indicated in Figure 2. An experiment involving just the central design points in Figure 2 ($P_1, P_2, ..., P_5$) is capable of providing information needed to model linear effects of cure temperature and $\log_{10}$(cure time) as well as the interaction between these two factors. This basic pattern was supplemented with two other design points: low temperature, high time (P_6) and high temperature, low time (P_7). The purpose of experimenting at these additional points is to explore processing conditions well outside the anticipated optimal range. Experimentation at these points enables an assessment of the potential for low temperature curing (P_6) and a very fast cure (P_7). The anticipated effects of cure time on material properties lessen as the cure time increases. Thus, the logarithm of cure time (rather than cure time) was selected as the appropriate factor to study.

Figure 2. Experimental Process Levels



For each polyurethane system, the basic experimental pattern consists of $3 \times 7 = 21$ unique conditions defined by all combinations of the composition and processing factors. Batches of material (each consisting of 2 plaques) prepared by processing at these 21 conditions were used to assess the effects of the various factors. Appendices 1, 2, 3, and 4 present the complete experimental plan (23 trials), including the order in which these materials were prepared. This run order was randomized so that valid conclusions regarding the effects of the factors could be obtained, even in the presence of unknown time-related phenomena. The purposes of the additional two batches of material (trials numbered 1 and 23), prepared at the centerpoint condition (compositional midpoint, 144°F, and 13.8 hours) are to assess process drift and to characterize batch-to-batch variability. The two plaques from each batch were used to assess the variability within a batch. Specimens taken from each plaque were subjected to the various property tests.

V. Analysis of Experimental Data

Appendices 1, 2, 3, and 4 summarize the experimental results. For each experimental condition, specified by the prepolymer/curative pair, curative level, and cure schedule, summary values for each of the four responses (pot life, T_g, hardness, and tear strength) are displayed by run order. The summary value for hardness reflects the average of three measurements taken on each of the two plaques. The summary value for tear strength reflects the average of the median tear strengths of each of two plaques. The median tear strength of a plaque is computed from five independent measurements. The median tear strength was used as a basis for the summary value (as opposed to the mean) as it is less sensitive to discrepant measurements.

Figures 3-6 provide graphical illustrations of the experimental results provided in Appendices 1-4. Each of these figures provides a straightforward means to assess the effects of composition and processing on each of the four responses studied. Furthermore, these figures allow for a direct comparison of the four polyurethane systems.

Historical data for glass transition temperature and hardness from the A. J. Quant Chart (May 1971) are as follows:

	Tg(°C):	Hardness (Shore A):
Adiprene L-100/Cyanacure:	-55	92
EN-7:	-77	86

Tear strength data were not included in the Quant Chart. The minimum requirements for tear strength are given in the material specifications (MS 2526812 for Adiprene L-100/ Cyanacure and MS 2519603 for EN-7):

	Tear Strength (pli):
Adiprene L-100/Cyanacure:	350 min.
EN-7:	200 min.

Figure 3 displays the ***pot life*** (in minutes), as determined by the operator, for each polyurethane system by curative level and curing condition. Across the four polyurethane systems, the intuitively obvious effect of curative level on pot life is apparent (i.e., pot life decreases as the curative level increases). From Figure 3, it is also clear that formulations involving the Adiprene L-100/ Cyanacure system (control) provide the shortest pot life (10-20 minutes). At the intermediate level of curative, the three other systems exhibit similar pot lives (30-40 minutes). Thus, each of the three alternative systems has an improved pot life when compared to the control system (Adiprene L-100/Cyanacure). Of these three low-TDI systems, the pot life of Adiprene L-100/ Ethacure 300 shows somewhat less sensitivity to high levels of curative than the other two systems.

As illustrated in Figure 4, the ***hardness*** is affected by the selection of the curative as well as the prepolymer. Polyurethanes formulated with Adiprene L-100 as a prepolymer are harder than those formulated with Airthane PET 90-A. Further, polyurethanes formulated with Cyanacure as the curative are harder than those formulated with Ethacure 300. Thus, Adiprene L-100/ Cyanacure materials are the hardest (90 to 95 Shore A), while Airthane PET 90-A/ Ethacure 300 materials are the softest (81 to 86 Shore A). Over the ranges of curative levels studied, for each polyurethane material, the hardness is maximized (and falls in the range of the historical data) when the curative level is at an intermediate value. The precise curative levels that maximize hardness are unknown. If needed, additional experimentation could precisely identify those levels. Nevertheless, the optimal curative levels are likely to be quite close to the intermediate levels that were observed.

As illustrated in Figure 5, the glass transition temperature (T_g) varies widely among systems and does not appear to depend much on the curative, curative level, or cure schedule. The polyurethane systems formulated with the Adiprene L-100 prepolymer exhibit significantly higher values of T_g than systems formulated with the Airthane PET 90-A prepolymer. Thus, both Airthane PET 90-A systems are improvements over the control system. The Adiprene L-100/ Ethacure 300 formulations exhibit slightly higher values of T_g than the Adiprene L-100/ Cyanacure formulations. Except when using relatively low levels of curative, the T_g appears to be insensitive to the cure schedule. However, when the curative level is low, it appears that curing at P_7 (very high temperature [212 °F] for a short time [4 hours]) tends to increase the T_g slightly.

Figure 6 displays the ***tear strengths*** of the various materials. Over the ranges of curative levels studied, the tear strength is maximized for an intermediate level of curative. In general, averaged over all conditions, the Adiprene L-100/ Ethacure 300 formulations produced the highest tear strengths. When an intermediate level of curative was used, tear strengths of around 700 pli were observed for the Adiprene L-100/ Ethacure 300 formulations processed at each of the seven conditions. Even with high levels of Ethacure 300, the Adiprene L-100/ Ethacure 300 formulations exhibited tear strengths of about 500 pli. It was also possible to produce tear strengths of about 700 pli with the control system (Adiprene L-100/ Cyanacure). However, the control system exhibited more sensitivity to the level of curative compared to the other systems. For high levels of Cyanacure, the tear strengths of Adiprene L-100/ Cyanacure materials were reduced to about 350 pli, which is the minimum requirement given in the material specification (MS 2526812).

From an overall perspective, significant variations in material properties (pot life, T_g, hardness, and tear strength) were introduced by modifying the curative (type and level). In general, varying the cure schedule (over the range considered) had little effect on material properties, except when the curative was at a low level (see solid curves in Figures 3-6 connecting X's). With low levels of curative, more time and temperature are required to cure the material, so that some processing conditions may have resulted in an undercure. Hence, the cured material (and associated properties) are more sensitive to variations in the cure schedule when the level of curative is low.

VI. Comparison of the Alternative Systems with the Control System

The viability of the three alternative low-free-TDI polyurethane systems (Adiprene/Ethacure, Airthane/Cyanacure, and Airthane/Ethacure) for applications can be established by comparing their material properties with those of the control system (Adiprene/ Cyanacure). By varying the curative level, it is possible (to some extent) to optimize the materials for a particular property, say tear strength. Note, however, that there will likely be tradeoffs when one is trying to optimize multiple properties simultaneously. That is, by optimizing one property (say pot life, which increases with decreasing amounts of curative) one might be deoptimizing another property (say hardness).

- With respect to pot life, it appears that each of the three alternative systems can provide some improvement over the control system.

- Alternative materials were somewhat less hard than the control materials which exhibited hardnesses in the range from 90-95 Shore A. Nevertheless, even the Airthane/Ethacure materials (which were these least hard of the systems studied) exhibited a Shore A hardness of between 80 and 90, depending somewhat on the curative level. For most applications, this small decrease in hardness is considered to be unimportant.

- Materials developed with the Adiprene prepolymer (the control system and the Adiprene/Cyanacure system) exhibited somewhat higher values for T_g than the two Airthane-based systems. Thus, the lower T_g values of the Airthane-based systems provide these systems with an advantage over the Adiprene-based systems when the materials are to be used in applications involving low storage/use temperatures.

- Generally, the Adiprene-based materials (including the control system) exhibited higher tear strengths than the Airthane/Ethacure materials. For a fixed material, however, the tear strength depends significantly on the curative level.

VII. Conclusion

In conclusion, this material characterization study has shown three low-free-TDI polyurethane systems to be viable replacements for Adiprene L-100/Cyanacure and EN-7. As a result of the statistical analysis, we were able to estimate the optimum formulations for each of the systems studied. The optimum formulation for Airthane PET 90-A/Ethacure 300 (100:9.0) will be used in making samples for the Aging Study discussed in the Future Work section. Furthermore, this study has provided valuable data by defining the boundaries within which the processing parameters must be to ensure good product. This information will allow us to conduct effective troubleshooting in future applications where errors have occurred in processing polyurethane products. When looking for a polyurethane for a specific application, one should examine the material properties of each system and compare these to the requirements of the application.

VIII. Future Work Includes Aging Study

A thermal aging study has been initiated for Airthane PET 90-A/ Ethacure 300, using EN-7 and Adiprene L-100/ Cyanacure as the controls. The samples will be aged for 2 years in an oven at a constant temperature of 135°F. Testing will be conducted at different times during the aging study and will include: hardness, glass transition temperature, tear strength, outgassing, and electrical properties.

Figure 3 - Pot Life (minutes) versus Composition and Processing Condition*

*Refer to Figure 2

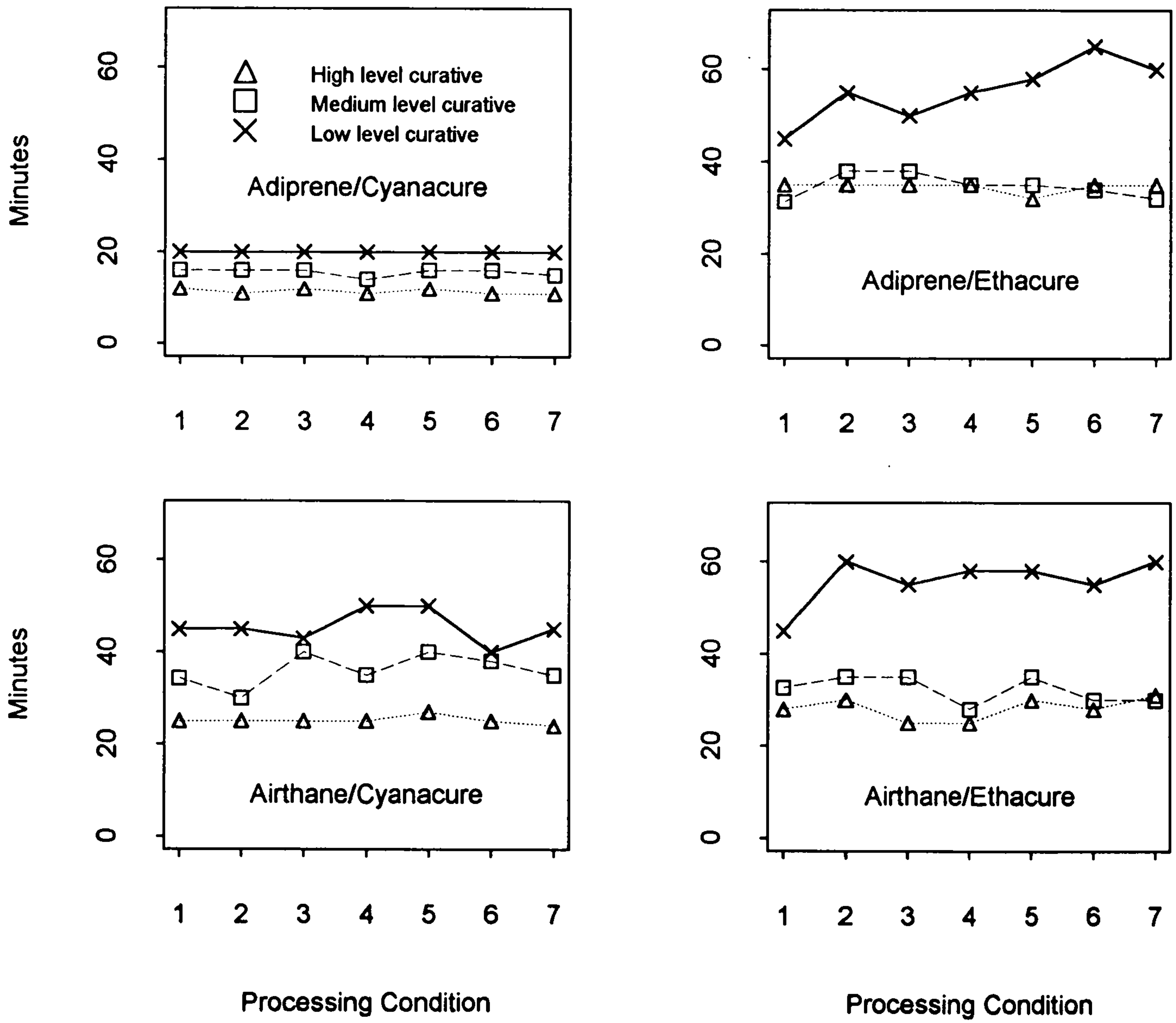


Figure 4 - Hardness (Shore A) versus Composition and Processing Condition*

*Refer to Figure 2

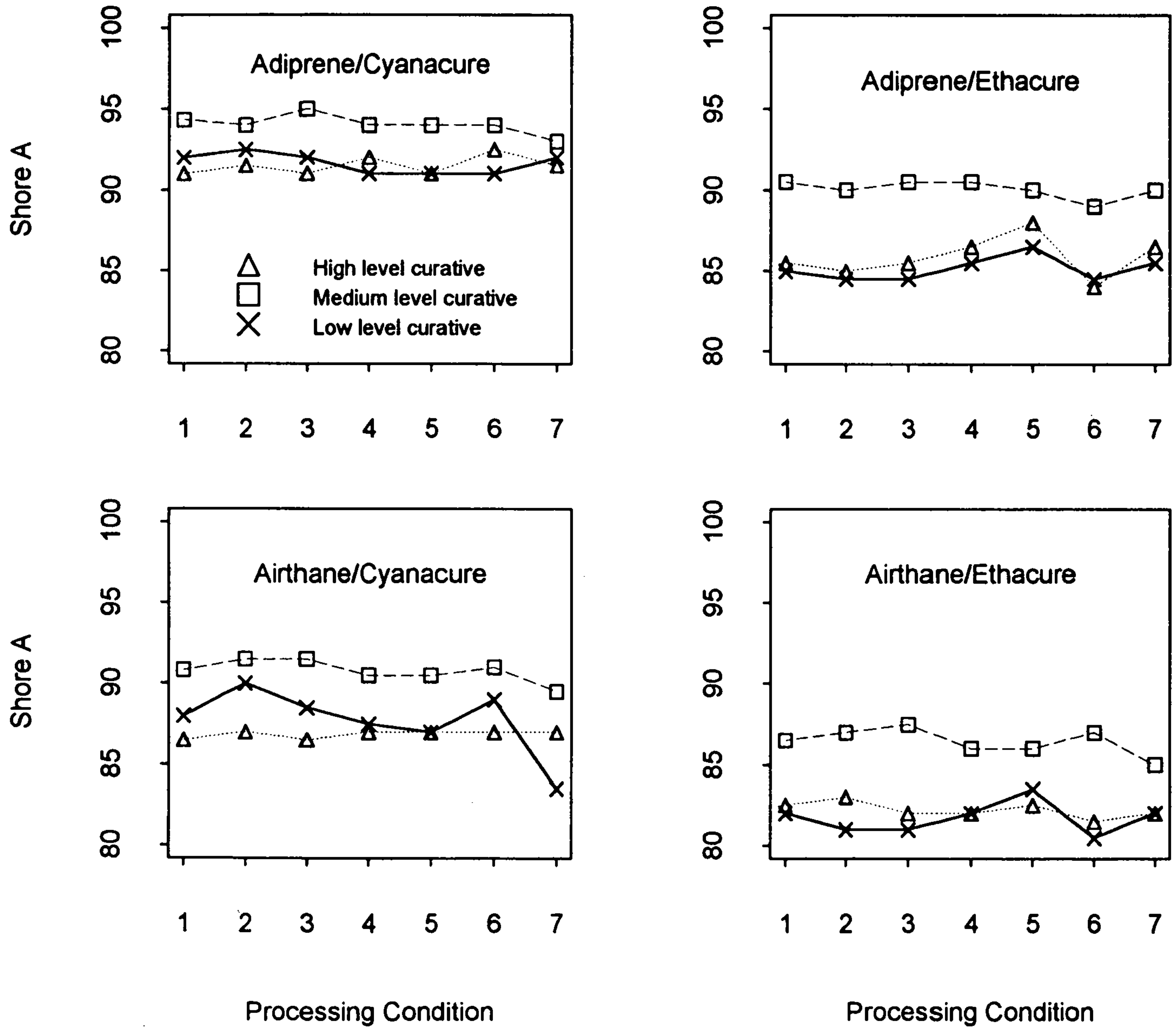


Figure 5 - Tg (degrees C) versus Composition and Processing Condition*

*Refer to Figure 2

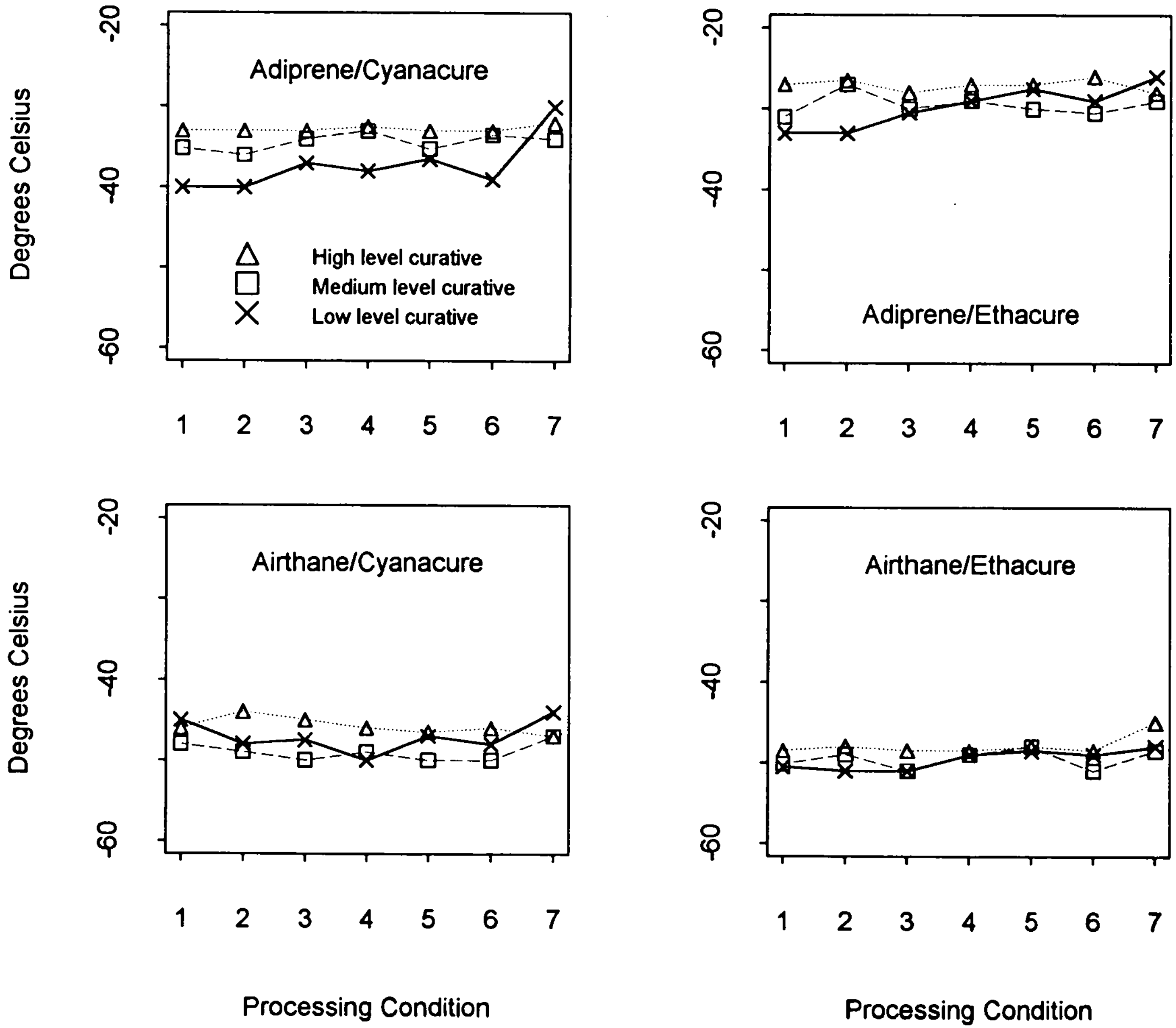
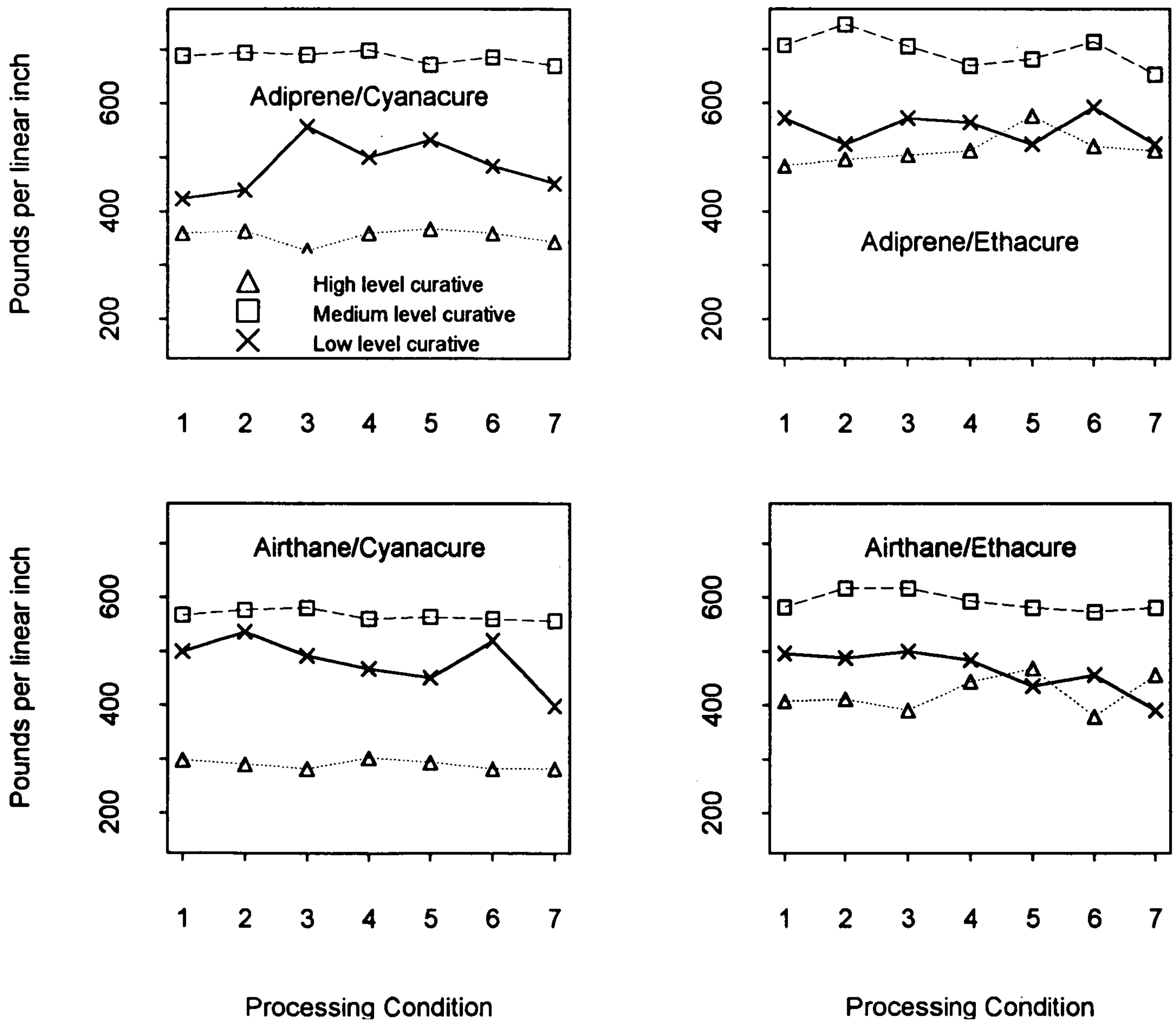


Figure 6 - Tear Strength (pounds per linear inch) versus Composition and Processing Condition*

*Refer to Figure 2



APPENDIX 1 - Adiprene/Cyanacure Data

Run Order	Parts Cyanacure	Time (hours)	Temperature (°F)	Pot Life (minutes)	T_g (°C)	Hardness (Shore A)	Tear Strength (pli)
1	14.1	13.80	144	16	-34	94	685
2	14.1	4.00	212	15	-34	93	669
3	14.1	7.43	178	14	-33	94	698
4	10.8	7.43	110	20	-37	92	556
5	17.5	4.00	212	11	-32	91.5	343
6	17.5	7.43	178	11	-32.5	92	359
7	10.8	48.00	75	20	-39	91	484
8	17.5	13.80	144	12	-33	91	359
9	17.5	25.60	178	12	-33	91	367
10	14.1	25.60	110	16	-36	94	694
11	17.5	7.43	110	12	-33	91	327
12	14.1	13.80	144	16	-36	94.5	685
13	17.5	25.60	110	11	-33	91.5	363
14	10.8	4.00	212	20	-30	92	452
15	10.8	7.43	178	20	-38	91	500
16	14.1	25.60	178	16	-35	94	671
17	14.1	7.43	110	16	-34	94	690
18	10.8	25.60	110	20	-40	92.5	440
19	10.8	25.60	178	20	-36.5	91	532
20	17.5	48.00	75	11	-33	92.5	359
21	14.1	48.00	75	16	-33.5	94	685
22	10.8	13.80	144	20	-40	92	423
23	14.1	13.80	144	16	-35.5	94.5	694

APPENDIX 2 Airthane/Cyanacure Data

Run Order	Parts Cyanacure	Time (hours)	Temperature (°F)	Pot Life (minutes)	T_g (°C)	Hardness Shore A)	Tear Strength (pli)
1	12.3	13.80	144	35	-50	91.5	581
2	12.3	4.00	212	35	-47	89.5	556
3	12.3	7.43	178	35	-49	90.5	560
4	9.3	7.43	110	43	-47.5	88.5	492
5	15.2	4.00	212	24	-47	87	282
6	15.2	7.43	178	25	-46	87	302
7	9.3	48.00	75	40	-48	89	520
8	15.2	13.80	144	25	-46	86.5	298
9	15.2	25.60	178	27	-46.5	87	294
10	12.3	25.60	110	30	-49	91.5	577
11	15.2	7.43	110	25	-45	86.5	282
12	12.3	13.80	144	38	-46	90	540
13	15.2	25.60	110	25	-44	87	290
14	9.3	4.00	212	45	-44	83.5	399
15	9.3	7.43	178	50	-50	87.5	468
16	12.3	25.60	178	40	-50	90.5	565
17	12.3	7.43	110	40	-50	91.5	581
18	9.3	25.60	110	45	-48	90	536
19	9.3	25.60	178	50	-47	87	452
20	15.2	48.00	75	25	-46	87	282
21	12.3	48.00	75	38	-50	91	560
22	9.3	13.80	144	45	-45	88	500
23	12.3	13.80	144	30	-48	91	581

APPENDIX 3 Adiprene/Ethacure Data

Run Order	Parts Cyanacure	Time (hours	Temperature (°F)	Pot Life (minutes)	T_g (°C)	Hardness (Shore A)	Tear Strength (pli)
1	11.0	13.80	144	30	-30	90.5	706
2	11.0	4.00	212	32	-29	90	653
3	11.0	7.43	178	35	-29	90.5	669
4	8.4	7.43	110	50	-30.5	84.5	573
5	13.6	4.00	212	35	-28	86.5	512
6	13.6	7.43	178	35	-27	86.5	512
7	8.4	48.00	75	65	-29	84.5	593
8	13.6	13.80	144	35	-27	85.5	484
9	13.6	25.60	178	32	-27	88	577
10	11.0	25.60	110	38	-27	90	746
11	13.6	7.43	110	35	-28	85.5	504
12	11.0	13.80	144	32	-31	90.5	685
13	13.6	25.60	110	35	-26.5	85	496
14	8.4	4.00	212	60	-26	85.5	524
15	8.4	7.43	178	55	-29	85.5	565
16	11.0	25.60	178	35	-30	90	681
17	11.0	7.43	110	38	-30	90.5	706
18	8.4	25.60	110	55	-33	84.5	524
19	8.4	25.60	178	58	-27.5	86.5	524
20	13.6	48.00	75	35	-26	84	520
21	11.0	48.00	75	34	-30.5	89	714
22	8.4	13.80	144	45	-33	85	573
23	11.0	13.80	144	32	-32	90.5	730

APPENDIX 4 Airthane/Ethacure Data

Run Order	Parts Cyanacure	Time (hours)	Temperature (°F)	Pot Life (minutes)	T_g (°C)	Hardness (Shore A)	Tear Strength (pli)
1	9.5	13.80	144	30	-50	87	577
2	9.5	4.00	212	30	-48.5	85	581
3	9.5	7.43	178	28	-49	86	593
4	7.2	7.43	110	55	-51	81	500
5	11.8	4.00	212	31	-45	82	456
6	11.8	7.43	178	25	-48.5	82	444
7	7.2	48.00	75	55	-49	80.5	456
8	11.8	13.80	144	28	-48.5	82.5	407
9	11.8	25.60	178	30	-48	82.5	468
10	9.5	25.60	110	35	-49	87	617
11	11.8	7.43	110	25	-48.5	82	391
12	9.5	13.80	144	37	-50	85	597
13	11.8	25.60	110	30	-48	83	411
14	7.2	4.00	212	60	-48	82	391
15	7.2	7.43	178	58	-49	82	484
16	9.5	25.60	178	35	-48	86	581
17	9.5	7.43	110	35	-51	87.5	617
18	7.2	25.60	110	60	-51	81	488
19	7.2	25.60	178	58	-48.5	83.5	435
20	11.8	48.00	75	28	-48.5	81.5	379
21	9.5	48.00	75	30	-51	87	573
22	7.2	13.80	144	45	-50.5	82	496
23	9.5	13.80	144	31	-50.5	87.5	573

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